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Design a Power System of 1760W Based on a Twin Inverter and a Fuzzy Logic Controller

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Abstract
The increasing demand for electricity due to population expansion has led to frequent interruptions in electrical power, so there are backup power lines everywhere, especially in the sectors of education, health, banking, transportation and communications. DC sources are beginning to become widely spread in terms of low maintenance requirements, no need for refueling, and no pollutant emission in these institutions. The problems of DC systems are; losses in DC system components, and change in output voltage as loads change. This research presents a power system that generates 1760W AC power from batteries bank, the system consists of a twin inverter to reduce losses in switches and filters, and thus improving the efficiency and the power factor of the system, and fuzzy logic controllers to regulate the output voltage of the converter and inverter. Modeling and simulation in MATLAB / Simulink showed obtaining a constant load voltage with acceptable values of total harmonics distortion (THD) under different conditions of loads and batteries.

Keywords
Synchronous boost converter, Twin inverter, Fuzzy logic controller, Gaussian membership functions, Total harmonics distortion(THD).

I. INTRODUCTION

Among the most important reasons that lead to power outages: the amount of electric power generation is insufficient to cover the increasing demand, especially in the summer, the increase in voltage drop in transmission lines due to high temperatures, and the absence of energy quality improvement systems such as; Static Synchronous Compensator (STATCOM), Dynamic Voltage Restorer (DVR), Unified Power Flow Controller (UPFC), Active Filter (AF), and Passive Filter (PF), plus a lack of diverse power sources and a total reliance on fossil fuels for electric power generation. Some consumers prefer to use direct current sources such as solar panels and batteries, which are quiet and have low maintenance requirements, and due to the frequent breakdowns of diesel generators and the need for fuel. A large number of papers have been reported in the literature of converting DC to AC systems. Babaei [1] presented single phase cascaded multi - level inverter, Ellaban [2] introduced Z-source inverter, Henago [3] presented using series/parallel switches DC voltage source inverter, Sandeep [4] established neutral-point nine level inverter, Kim [5] presented two-stage three-level grid-connected photovoltaic inverter, Kangarlu [6] introduced cascaded multilevel inverter using series connection of sub-multilevel inverter, Le [7] presented six level inverter topology for medium voltage applications. PI controller, ANN(artificial neural network), Fuzzy logic controller, Fuzzy neural controller, PWM, SPWM, and SVPWM techniques have been used to get a stable output voltage under different load conditions with minimum values of the total harmonics distortion (THD), and the researchers focused on reducing switches losses and establishing a transformer less inverter to reduce the size and the weight of the system [8]. This research focuses on obtaining a power system with a stable voltage under different load and batteries conditions with a minimum values of the THD and reducing losses in filters in addition to switches losses to improve the efficiency and the power factor of the inverter. A twin inverter providing more than one line to feed loads is used to reduce filters and switches losses. In order to obtain a stable output voltage un-

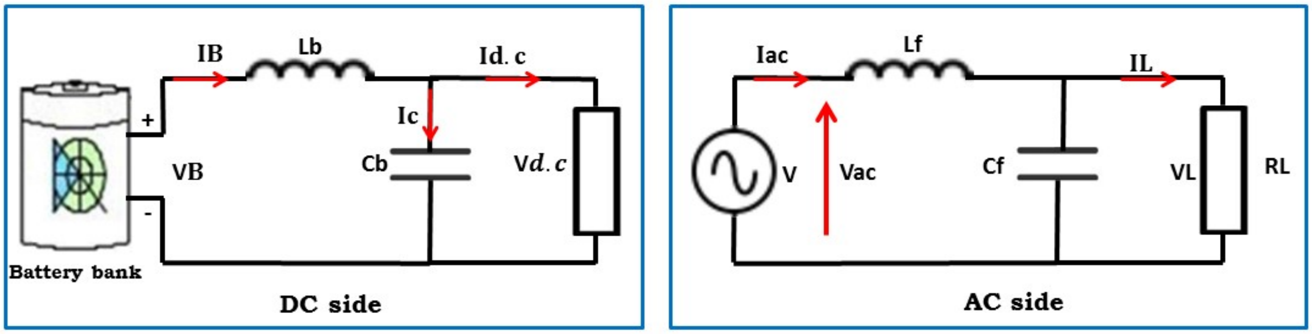

Fig. 1. Power system equivalent circuit diagram.

der various conditions, the control system is designed based on a fuzzy logic controller, which is tolerant of inaccurate data, can model nonlinear functions of arbitrary complexity, and relies on natural language, so the number and variety of engineering applications of fuzzy logic have increased significantly. Gaussian membership functions are used because of their smoothness and brevity of notation, which is a popular method for defining fuzzy sets, and has the advantage of being smooth and non-zero at all points [9]. The synchronous converter is used instead of transformer to prevent the converter capacitor from short circuit, as the two switches are never operated together, and the power losses in the mosfet are less than the losses in the diode [10]. Schematic diagram of the conversion of DC power into AC power, mathematical model, principle operation of the twin inverter, determination of converter parameters, and the construction of the fuzzy logic controller are presented in this paper.

II. Mathematical Model

Fig. 1 demonstrated the equivalent circuit of the power system. The mathematical representation of the power system is as following [11]; Kirchhoff's voltage law (KVL) applied to the DC side (the sum of voltage in a closed loop is zero)

$$V_{d.c} = (V_B \cdot D + V_L) \cdot \eta_c \tag{1}$$

where: V_B is the battery voltage, D represents the duty cycle, and η_c is the boost converter efficiency.

$$V_{d.c} = (V_B \cdot D + D \cdot I_B \cdot 2\pi f_{\text{sb}} L_{\text{b}}) \cdot \eta_c \tag{2}$$

Here, I_B is the battery current, f_{sb} represents the switching frequency of the boost converter, and L_b is the inductor of the boost converter. Applying Kirchhoff's current law(KCL) to the DC side.

$$I_{d.c} = (D \cdot I_B - I_c) \cdot \eta_c \tag{3}$$

$$I_{d.c} = (D \cdot I_B - 2\pi f_{\text{sb}} C_{\text{b}} (V_B \cdot D + D \cdot I_B \cdot 2\pi f_{\text{sb}} L_{\text{b}}) \cdot \eta_c) \cdot \eta_c \tag{4}$$

Applying (KVL) to the AC side

$$v + L_f \frac{di}{dt} - V_L = 0 \tag{5}$$

$$v + L_f \frac{di}{dt} = V_L \tag{6}$$

$$v = v_{a.c} = V_{r.m.s} \tag{7}$$

$$V_{r.m.s} + L_f \frac{di}{dt} = V_L \tag{8}$$

$$V_{r.m.s} = \frac{V_{d.c}}{\sqrt{2}} \cdot m \cdot \eta_{\text{inv}} \tag{9}$$

$$V_{r.m.s} = 0.707 (V_B \cdot D + D \cdot I_B \cdot 2\pi f_{\text{sb}} L_{\text{b}}) \cdot \eta_c \cdot m \cdot \eta_{\text{inv}} \tag{10}$$

$$I_{r.m.s} = \frac{I_{d.c}}{\sqrt{2}} \cdot m \cdot \eta_{\text{inv}} \tag{11}$$

$$I_{r.m.s} = 0.707 \left(D \cdot I_B - 2\pi f_{\text{sb}} C_{\text{b}} (V_B \cdot D + D \cdot I_B \cdot 2\pi f_{\text{sb}} L_{\text{b}}) \cdot \eta_c\right) \cdot \eta_c \cdot m \cdot \eta_{\text{inv}} \tag{12}$$

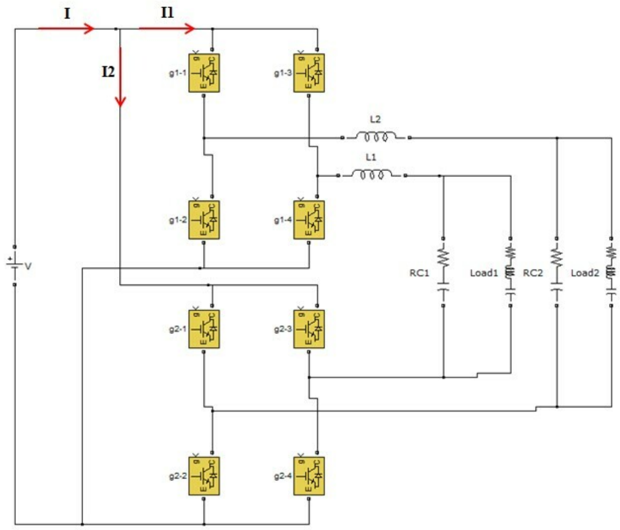

Fig. 2. The twin inverter.

$$V_L = 0.707(V_B \cdot D + D \cdot I_B \cdot 2\pi f_{\text{sb}} L_{\text{b}}) \cdot \eta_c \cdot m \cdot \eta_{\text{inv}} + L_f \frac{d}{dt}(0.707(D \cdot I_B - 2\pi f_{\text{sb}} C_{\text{b}} (V_B \cdot D + D \cdot I_B \cdot 2\pi f_{\text{sb}} L_{\text{b}}) \cdot \eta_c) \cdot \eta_c \cdot m \cdot \eta_{\text{inv}}) \quad (13)$$

$$I_L = \frac{V_L}{R} \quad (14)$$

In the above equations, C_{b} designates the capacitor of the boost converter, L_{f} denotes the inductor of the filter, m signifies the modulation index, and η_{inv} represents the inverter efficiency.

III. The Principle Operation of The Twin Inverter

The twin inverter consists of two bridges feeding two groups of loads, each load tied to a leg from the first bridge and a leg from the second bridge as depicted in Fig. 2. In the positive half cycle, current passes from the positive terminal of the source through g1-3 to load 1 and back to the negative terminal through g2-4, and from the positive terminal to the second load through g1-1 and back to the negative terminal through g2-2. In the negative half cycle, current from the positive terminal passes to the first load through g2-3 and back to the negative terminal through g1-4, and current feeds the second load from the positive terminal through g2-1 and returns to the negative terminal through g1-2. Table I shows the operation of IGBT transistors within 360 degrees.

Since the current is divided between the two bridges the losses will be reduced to a half as obvious in the basic formulas:
Losses in a single inverter (LSI) is:

$$\text{LSI} = I^2 (R_{\text{ac}} + R_{\text{dc}})_{\text{inductor}} + I^2 R_{\text{RC}} \quad (15)$$

Losses in the twin inverter (LTI) is:

$$\text{LTI} = 2\left[\left(\frac{I}{2}\right)^2 \cdot (R_{\text{ac}} + R_{\text{dc}})_{\text{inductor}} + \left(\frac{I}{2}\right)^2 R_{\text{RC}}\right] \quad (16)$$

$$= \frac{1}{2} I^2 \left[(R_{\text{ac}} + R_{\text{dc}})_{\text{inductor}} + R_{\text{RC}}\right] \quad (17)$$

Losses reduction leads to improved inverter efficiency (η_{inv})

$$\eta_{\text{inv}} = \frac{P_o}{P_o + P_{\text{losses}}} \quad (18)$$

and improves the power factor of the inverter (p.f)

$$\text{p.f} = \frac{P_o}{S} \quad (19)$$

and reduces the amount of heat that power supplies have to dissipate

$$\Delta T \propto I^2 \quad (20)$$

In addition, the increase in the current of nonlinear loads such as computers, printers, variable speed drives, and power conversion systems leads to an increase in harmonics, so nonlinear loads can be divided into groups and feed them using the twin inverter to protect the system from increasing the harmonics.

IV. A Conversion Flow from The Dc Voltage to Ac Voltage

The power flow in the system is illustrated in Fig. 3, where:

$$\text{Converter output voltage} = \frac{V_i}{1 - D} \cdot \eta_c \quad (21)$$

$$\text{Converter output current} = \frac{I_i \cdot (1 - D)}{\eta_c} z \quad (22)$$

TABLE I.
IGTB Transistors in The On State Throughout 360° Degrees

0 - 180°	180° - 360°
g1-1, g2-2	**g2-1, g1-2**
g1-3, g2-4	**g2-3, g1-4**

The effective values of voltage and current (r.m.s)

$$\text{V and I (r.m.s)} = \frac{\text{DC values}}{\sqrt{2}} \quad (23)$$

The efficiency of the converter and inverter is 80%, the duty cycle of the boost converter is between (0.8 – 0.85) for stability operation of the converter [12], and the modulation index of the inverter (m) is between (0 – 1) [13]. The inductor and capacitor of the boost converter is determined depending on the equations [11, 14]:

$$L = \frac{V_i(V_o - V_i)}{f_s \cdot \Delta I \cdot V_o} \quad (24)$$

$$C = \frac{I_o(V_o - V_i)}{f_s \cdot \Delta v \cdot V_o} \quad (25)$$

Where:

$$\text{Current ripple}(\Delta I) = 5\% \text{ of the input current} \quad (26)$$

$$\text{Voltage ripple}(\Delta V) = 1\% \text{ of the output voltage} \quad (27)$$

Substitute:

$$\text{Input voltage} = 96\,\text{V},$$
$$\text{Input current} = 128\,\text{A},$$
$$\text{Initial duty cycle (D)} = 83\%,$$
$$\text{Output voltage} = 452\,\text{V},$$
$$\text{Output current} = 17.4\,\text{A},$$
$$\text{Switching frequency } (f_{sb}) = 5\,\text{kHz},$$
$$\text{Current Ripple}(\Delta I) = 6.4\,\text{A},$$
$$\text{Voltage Ripple}(\Delta V) = 4.52\,\text{V},$$

Result:

$$L = 2.36\,\text{mH},$$
$$C = 606\,\mu\text{F}.$$

V. Fuzzy Logic Controller

The general construction of the FLC consists of five steps [15, 16]: Fuzzify Inputs, Apply Fuzzy Operator, Apply Implication Method, Aggregate All Outputs, and Deffuzification.

1. **Fuzzify Inputs:** It converts a crisp input signal, error and change of error into fuzzy set by membership functions, the output is a fuzzy degree of membership functions (0 -1).
2. **Apply Fuzzy Operator:** the fuzzy operator (AND/ OR) is applied to obtain one number that represents the result of the antecedent (an input fuzzy set represented by a membership function) for the input that has more than one part.
3. **Apply Implication Method:** The consequent (an output fuzzy set represented by a membership function) is reshaped using a function associated with the antecedent. Fig. 4 shows the implication process.
4. **Aggregate All Outputs:** Aggregation is the process by which the consequent of each rule are combined into a single fuzzy set.
5. **Deffuzification:** The input of the defuzzification process is the aggregate of the consequent of all rules. The most popular defuzzification method is the centroid calculation, which returns the center of area under the curve as obvious in Fig. 5.

If μ_c is defined with continuous membership function, the center of gravity is:

$$\text{Center of Gravity} = \frac{\int \mu_c(x) \cdot x\,dx}{\int \mu_c(x)\,dx} \quad (28)$$

And if μ_c is defined with discrete membership function, the center of gravity is:

$$\text{Center of Gravity} = \frac{\sum_{i=1}^{n} \mu_c(x_i) \cdot x_i}{\sum_{i=1}^{n} \mu_c(x_i)} \quad (29)$$

The membership function that used in control theory is a Gaussian membership function which shown in Fig. 6, and it is defined by [17]:

$$\mu(x,c,s,m) = \alpha \exp\left[-\frac{1}{2}\left|\frac{x-c}{s}\right|^m\right] \quad (30)$$

Here: c is the center, s represents width, and m is fuzzification factor (e.g., m = 2).

VI. The Membership Functions and The Set of Linguistic Rules of the Controllers

A. DC Voltage Regulator Controller

The fuzzy logic controller of error and change of error consists of 3 linguistic variables as shown in Fig. 7. In output there are 5 linguistic variables as shown in Fig. 8. The rules linking among input signals (error and change of error) and output signal for the dc voltage regulator is as depicted in Table II, Where; N negative, Z zero, P positive, SN small negative, MN medium negative, SP small positive, MP medium positive.

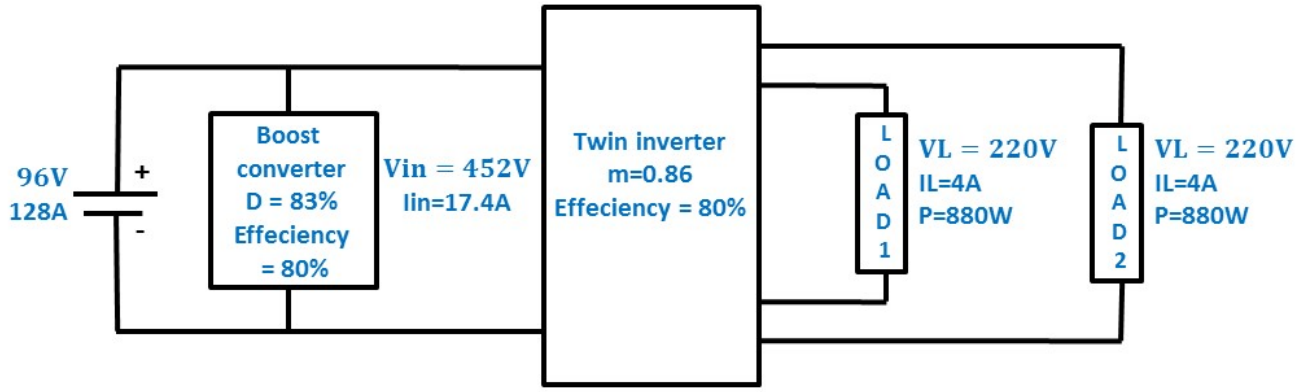

Fig. 3. The Conversion Flow from DC Voltage to AC Voltage.

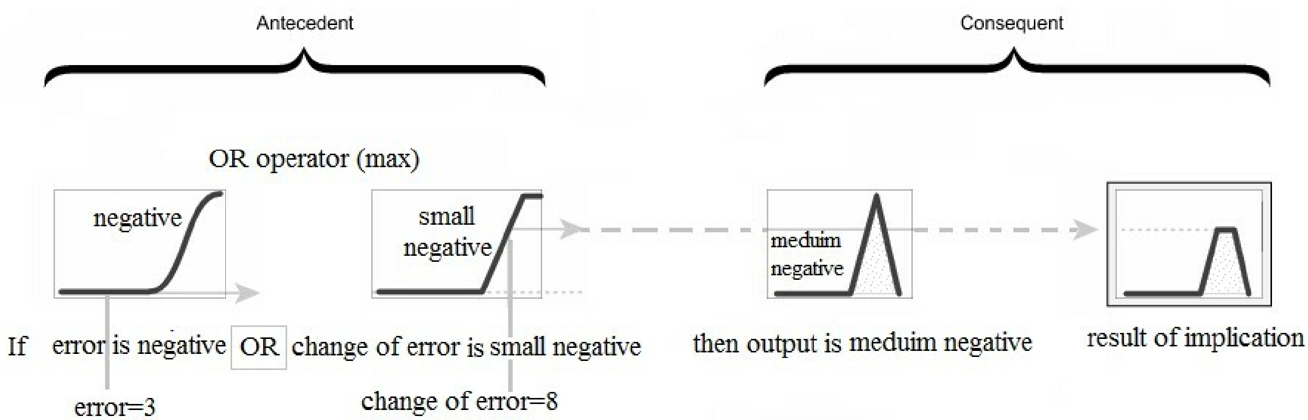

Fig. 4. The Implication of The One Rule.

TABLE II.
RULES SET FOR THE DC VOLTAGE CONTROLLER

e / Δe	SP	MP	P
SP	$SP1$	$SP2$	$MP1$
MP	$SP2$	$MP1$	$MP2$
P	$MP1$	$MP2$	P

TABLE III.
RULES SET OF THE AC VOLTAGE CONTROLLER

e / Δe	N	Z	SP	MP	P
N	MN	SN	Z	SP1	SP2
Z	SN	Z	SP1	SP2	MP
P	Z	SP1	SP2	MP	P

B. AC Voltage Regulator Controller

The membership functions of the error signal consists of 5 linguistic variables as shown in Fig. 9. For change of error there are 3 linguistic variables as obvious in Fig. 10. For output signal there are 7 linguistic variables as shown in Fig. 11. The rules linking between input(error and change of error) and output signals of the ac voltage controller is demonstrated in Table III.

VII. MODELING AND SIMULATION

Simulation has been carried out under different loads conditions using the design in Fig. 12 which based on control systems shown in Fig. 13 and Fig. 14. Filters with an inductor of 25mH and a capacitor of 110uf have been chosen according to the basic formula of the filter design [18]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{31}$$

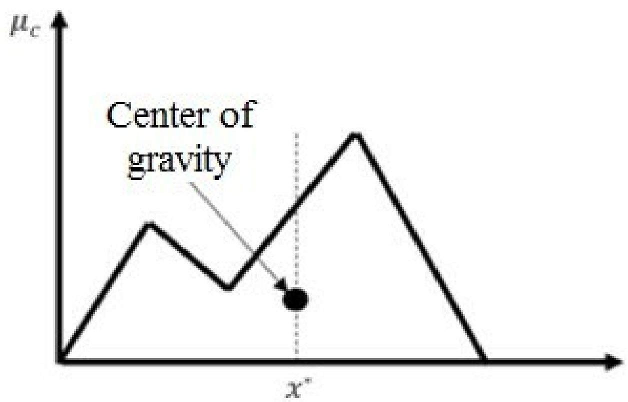

Fig. 5. The center of the area under the curve.

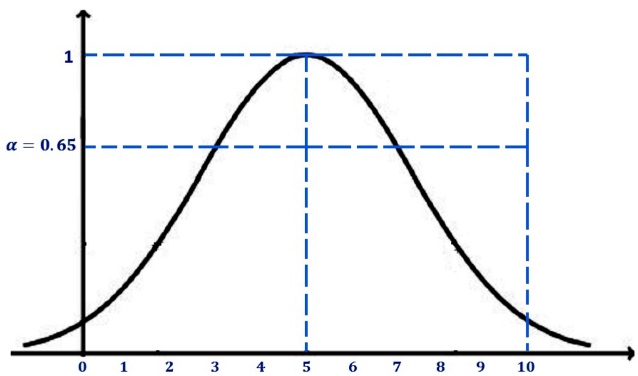

Fig. 6. The Gaussian membership function.

Since the loads are identical, the simulation results were taken for the first load. Fig. 15 demonstrated the batteries voltage, converter output, load voltage, and load current at the output power is 880W, Fig. 16 depicted the waveforms at the output power is 660W, Fig. 17 when the output power is 440W, and Fig. 18 when the output power is 220W. Fig. 19 depicted the simulation result when the battery voltage drops to 94v, and output power is 880W.

Simulation results demonstrated obtaining of 220v, 50Hz, with an acceptable limits of the total harmonics distortion (THD) according to the IEEE standard, which is less than 5% with the largest single harmonic no more than 3% of the fundamental voltage. Table IV shows the total harmonics distortion (THD) which are obtained from the FFT(Fast Fourier Transform) algorithm using powergui tool in MATLAB program.

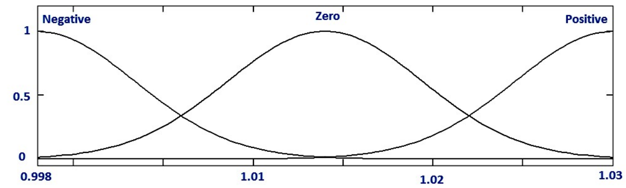

Fig. 7. The membership function of error and change of error signals of The Dc voltage regulator.

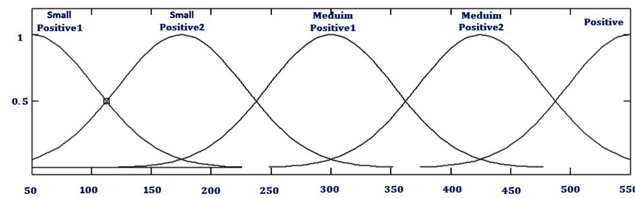

Fig. 8. The membership function of output signal of the Dc voltage regulator.

VIII. Conclusion

Fuzzy logic is easy and efficient to work with nonlinear systems, preferably with as few membership functions as possible to get a faster response time. Twin inverter technology is an advanced form of the inverter, as it ensures less noise, less energy consumption, and less fluctuations [19], because the current at the input and at the output of the inverter is divided between the two bridges, which leads to a decrease in the losses to a half, and thus reducing the rise in temperatures, and improve the efficiency and the power factor of the inverter, therefore, this technology is used in modern air conditioners to operate more than one compressor without connect it in parallel, in addition to the possibility of making them rotate in opposite directions [20]. Diversity of electrical power sources plays a vital role in obtaining a reliable electrical power, such as DC sources for small loads, and AC sources without fuel for large loads such as concentrated solar power (CSP) systems, and thermal solar power (TSP) systems.

Conflict of Interest

The author has no conflict of relevant interest to this article.

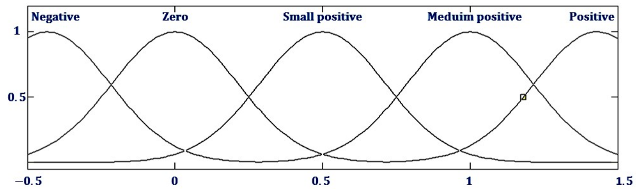

Fig. 9. The membership functions of the error signal of the Ac voltage regulator.

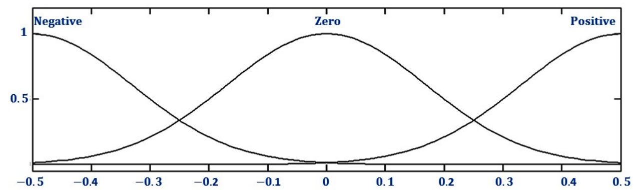

Fig. 10. The membership function of the change of error signal of the Ac voltage regulator.

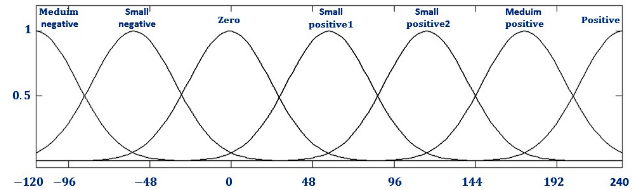

Fig. 11. The membership functions of output signal of the Ac voltage regulator.

TABLE IV.
TOTAL HARMONICS DISTORTION (THD) OF LOAD VOLTAGE AND CURRENT UNDER DIFFERENT LOADS AND BATTERY CONDITIONS

Load	THD% of Load Voltage	THD% of Load Current
D.C Voltage = 96V		
880W	1.05	0.45
660W	1.52	0.89
440W	1.82	0.81
D.C Voltage = 94V		
880W	1.23	0.85

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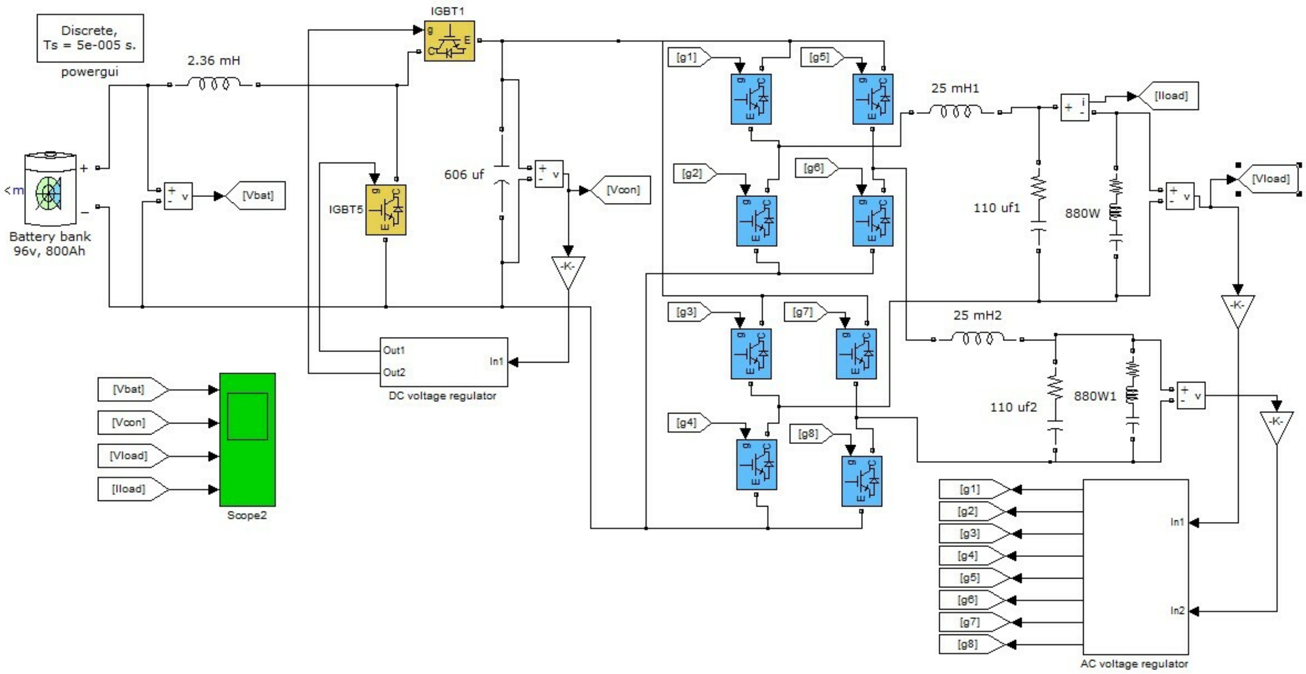

Fig. 12. The modeling of the electrical power system.

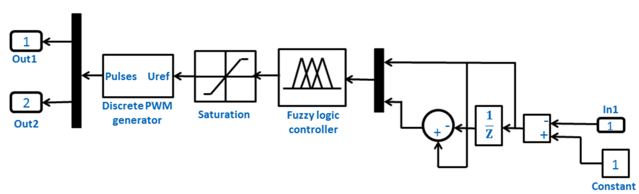

Fig. 13. The modeling of the Dc voltage regulator.

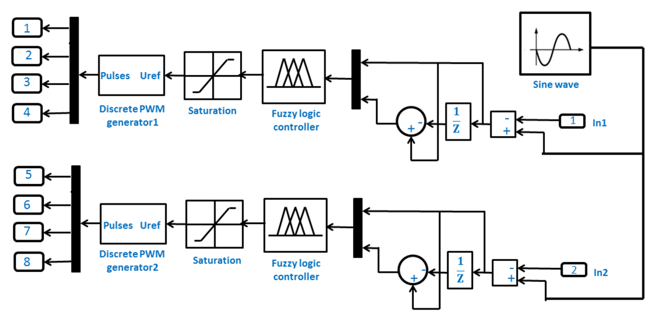

Fig. 14. The modeling of the Ac voltage regulator.

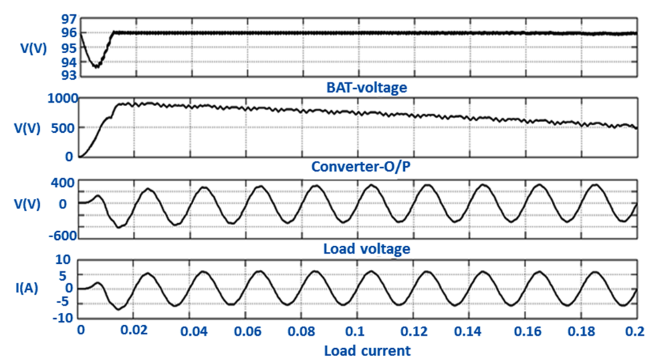

Fig. 15. The Waveforms Output at 880W Output Power.

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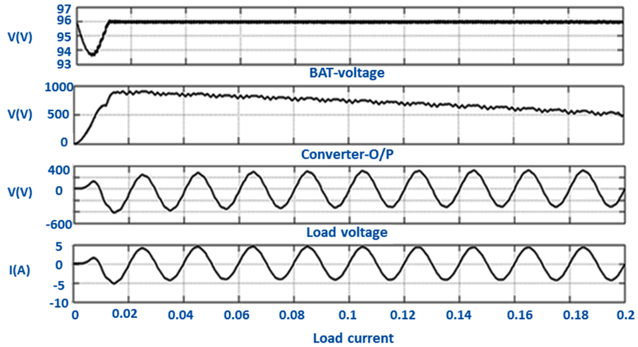

Fig. 16. The waveforms output at 660W output.

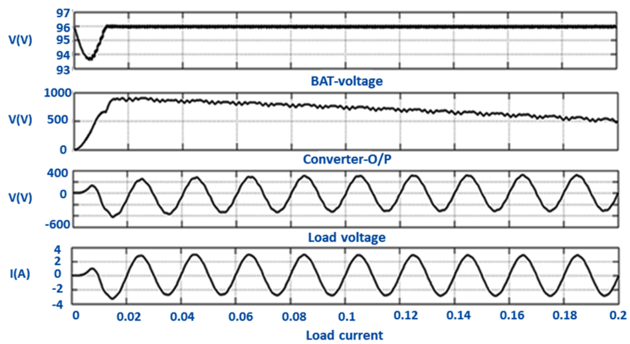

Fig. 17. The waveforms output at 440W output power.

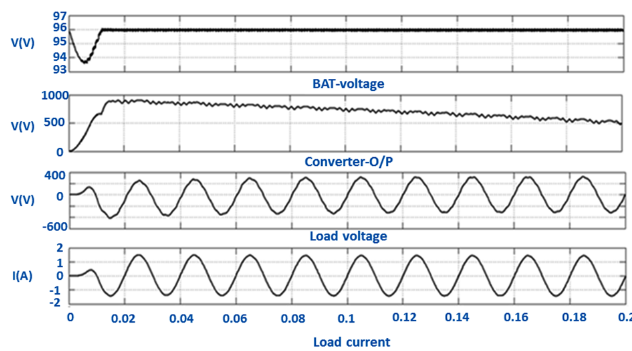

Fig. 18. The waveforms output at 220W output power.

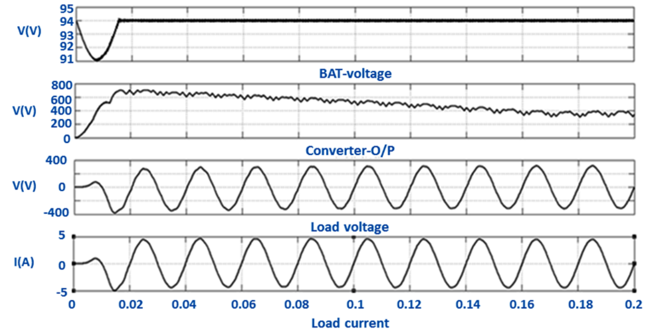

Fig. 19. The waveforms output at input voltage 94v, and output power 880W.

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